N90-28286

# CIRRUS RADIATIVE CHARACTERISITICS and the RADIATIVE IMPACT of SMALL PARTICLES

Paul W. Stackhouse Jr., Grame L. Stephens and S.K. Cox

*Department of Atmospheric Science, Colorado State University*

*Fort Collins, Colorado 80523*

## 1 Introduction

An understanding of the way radiation interacts with clouds is vital for understanding the sensitivity of the earth's climate to both natural and anthropogenic changes in the atmosphere. Cirrus clouds are thought to be an important modulator of climate sensitivity (see Manabe and Strickler, 1964; Cox, 1973 and Stephens and Webster, 1981 among others). Stephens *et al.* (1989) show the that the feedback effect of cirrus on climate can be positive or negative depending upon the microphysics and scattering properties of the cloud. These properties of cirrus clouds are not well understood partly because of their thin tenuous nature and partly because of their microphysical properties. The high altitude and cold temperatures within these clouds along with their transparency greatly increase the difficulty in which accurate measurements can be obtained and interpreted both by aircraft and remote sensing. Therefore, the understanding of the interaction of radiation in cirrus clouds is crucial to determining the ways in which these clouds interact with climate forcings.

The purpose of the present work is to examine the sensitivity of the radiative budgets of cirrus cloudiness to their microphysical composition and the environments in which they occur. Especially important is the impact of small particles on the radiative properties of cirrus. Remote sensing estimates of the effective crystal size of cirrus and *in situ* measurements show large differences up to 100 $\mu m$. Thus it becomes important to identify the sources of these differences. For this reason, simulations of actual FIRE cases are compared with the *in situ* radiative observations and inferences are made concerning the causes of the disprepancies.

## 2 Summary of the Radiative Transfer Model

A two stream radiative transfer band model for the solar (0.28 $\mu m$ - 3.8 $\mu m$) and infrared (3.8 $\mu m$ - 200.0 $\mu m$) wavelengths, is chosen and formulated in a way which allows for the consistent treatment of physical processes such as absorption and scattering by both molecules and particles which occur during the interaction of cloud and radiation (Stackhouse and Stephens, 1989). This is accomplished by solving the radiative transfer equation in terms of reflectance and transmittance coefficients and source terms dependent upon the optical depth, single scatter albedo and asymmetry factor of the optical media (Preisendorfer, 1976). The above three parameters represent the optical properties of molecules and particles for absorption and scattering processes and are weighted according to Slingo and Schrecker (1982). The particulate optical properties are determined using Mie solutions assuming equivalent diameter spheres from the particles measured during the IFO. Gaseous absorption is calculated using narrow band k-distribution data for $H_2O$, $CO_2$, $O_3$ and $O_2$ having resolutions of 20 $cm^{-1}$ and 50 $cm^{-1}$ in the infrared and solar wavelengths respectively. Sum of exponential fit data is used for the ultraviolet wavelengths less than 0.68 $\mu m$. Optical paths were computed using the simple pressure temperature scaling parameterization with constants given for each gas by Chou and Arking (1980), Chou and Arking (1981), Chou and Peng (1983) and Chou (1984). Parameterizations of Rayleigh scatter (Paltridge and Platt, 1976) and e-type absorption (Kneizys *et al.*, 1982) are also included.

## 3 Radiation Budgets: Cirrus in Various Atmospheres

Some of the phenomenological properties of cirrus clouds are investigated by simulating cirrus clouds imbedded in various atmospheres. The atmospheres in which cirrus are imbedded include the FIRE October 28, 1986 sounding and the McClatchey *et al.* (1972) Tropical and Subarctic Winter soundings. The 3 $km$ uniform cirrus is positioned such that cloud top corresponds to the tropopause height in each atmoshphere. Figure 1a summarizes the infrared radiation budget of cirrus and shows that the net radiative effect of cirrus is largely determined by surface-cloud base temperature difference (and thus altitude) and that heating (cooling) increases with increasing (decreasing) altitude. Also the net infrared radiative effect of the cirrus is seen to be more sensitive to cloud thickness with increasing height. Infrared spectral anaylsis reveals that: a) radiative heating dominates in the window region (8-12 $\mu m$) while cooling is dominated more in the far infrared ($\approx$ 15-200 $\mu m$), and b) the heating (cooling) of the window region (far infrared) increases in both magnitude and spectral width with increasing (decreasing) altitude.

In the solar wavelengths, simulations reveal that the net solar heating of the clouds decreases with decreasing cloud top altitude, and the changes in the spectral distribution of absorption as a function of altitude were mainly confined to the 2.6 - 2.9 $\mu m$ region where $CO_2$ is an active absorber.

The behavior of the radiative characteristics of cirrus in various atmospheres as deduced by the two-stream model agrees qualitatively to studies presented by Ackerman *et al.* (1988). Additionally, these results have profound climatological implications. It is not enough to know the amount or distribution of cirrus about the globe to understand their influence on the earth radiation budget. In order to understand the climatological effects of cirrus clouds, information regarding temperature and height as well as their distribution and microphysical characteristics must also be understood.

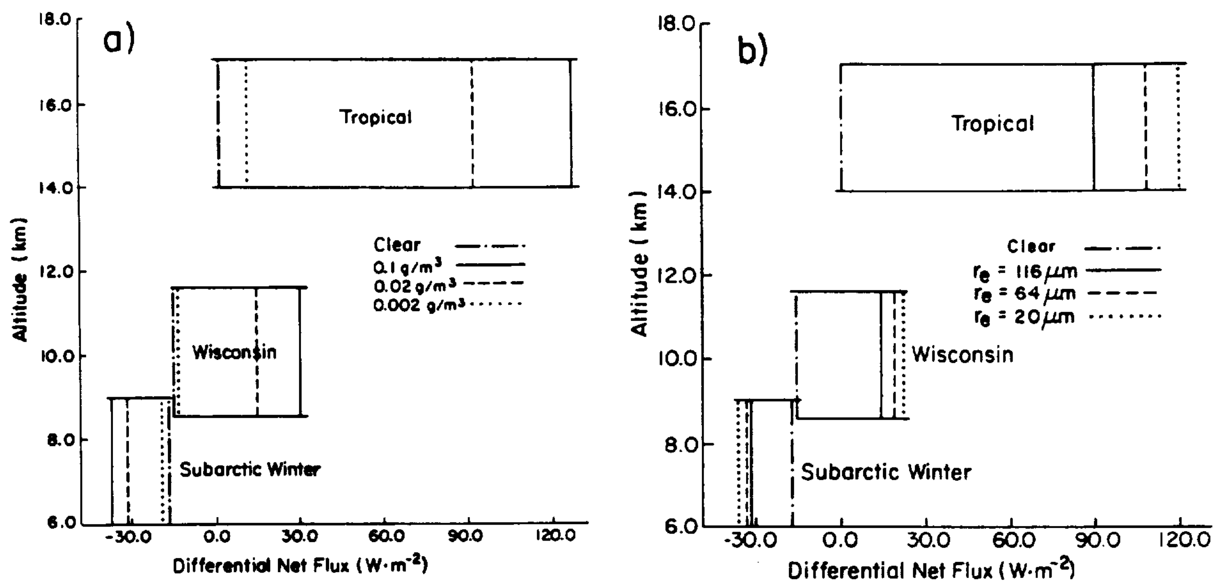


Figure 1: Schematic of the net infrared energy budgets of the three 3 $km$ uniform cirrus clouds situated in their respective atmospheres as shown with a) each having effective radii of 116 $\mu m$ for ice water contents as shown, b) each with ice water content of 0.002 $g \cdot m^{-3}$ having effective radii as shown.

# 4 Radiation Budgets: The Radiative Impact of Small Particles

Simulations assuming size distributions chosen from the FIRE observations and adjusted to include varying concentrations of small ice particles, are performed to evaluate the effect of these small particles on the radiative characteristics of cirrus clouds. Particles less than 50.0 $\mu m$ in size were not measured during the cirrus IFO but their presence is speculated (Heymsfield and Miller, 1989). Concentrations of particles less than 100 $\mu m$ in size are noted to be a source of uncertainty in understanding the radiative characteristics of cirrus clouds. To assess the importance of this uncertainty small particles are added to the observed crystal size distributions. The sensitivities of the model to the reduction of the effective radius of the observed crystal size distribution by the addition of small particles for constant cloud ice water content (IWC) is shown in Figure 1b. This figure shows that the sensitivity of the net infrared radiative budget of the cloud to the effective radius reductions, increases with increasing altitude.

Additional simulations, where the IWC is allowed to increase with the amount of small particles added to the size distribution, show that the effect of the IWC increase on the cloud radiative characteristics is small relative to the enhanced extinction casued by the presence small particles. All simulations show that the addition of relatively small concentrations of small particles results in a substantial enhancement of cloud radiative heating and cooling rates, cloud emittances and albedos. It can be concluded that appreciable differences between observations of cirrus radiative characteristics and theoretical calculations may be partly attributable to uncertainties of the amount of small particles in the observed size distributions.

# 5 Comparison to Observations

Comparisons between the thin cirrus case observed during the FIRE cirrus IFO on October 28, 1986 over the vicinity of Green Bay, Wisc. and simulations of this case are shown in Figure 2. The observations are derived from the upward and downward looking pyrogeometers and pyranometers flown on board the Sabreliner for this case. The irradiances are stratified along each aircraft leg corresponding to mean, thin and thick cloud cases after Smith *et al.* (1989). In addition, it was determined that two different types of clouds were observed corresponding to the north and south legs of the racetrack flight pattern. The curves on Figure 2a and b are the result of two cloud cases one of which contains the measured size distributions from the Sabreliner flight data and the other with the same measured size distributions plus an exponetial distribution of small particles less than 25 $\mu m$ in radius. The greatest amount of small particles comprising 20% of total ice water content, is assigned to the top cloud layer. This amount is decreased linearly toward cloud base where no small particles are assumed. In Figure 2c, a third cloud case corresponds to the resulting albedo when the asymmetry factor is artificially set to 0.7 for all the solar wavelengths. The comparisons shown in Figure 2a and b reveal that the simulated emittances of cirrus with the small particles added to cloud top agree most closely to the observed emittances. However, Figure 2c reveals that simulated albedos agree more closely to the observed albedoes with the addition of small particles but, the best agreement occurs when the asymmetry factor in the solar wavelengths is approximately 0.7. Thus the addition of small particles may be sufficient to explain discrepancies between the observed and simulated clouds in the infrared wavelengths but not in the solar wavelengths.

# 6 Conclusions

The radiative budgets of cirrus clouds are shown to be sensitive to the environment in which they are imbedded, the effective radii of the size distribution of which they are composed and their total ice water content. The comparison between the observations and simulations show that: a) underestimations of the infrared emittances are perhaps largely due to the overestimation of the effective cirrus crystal size which, may be traced to both the equivalent diameter sphere approximation and the underestimation of particles smaller than 100 $\mu m$ by observations and b) model underestimation of solar albedos is perhaps due in part to the overestimation of the asymmetry parameter as a result of the assumption of spherical particles.

It is clear from these results that the uncertainties involved in the estimation of the scattering properties of ice clouds remain one of the major hurdles that separates the agreement between the observations and simulations. Until the scattering properties of cirrus clouds are better understood, the interactions of radiation with microphysical parameters in the life cycle of these clouds will remain somewhat of a mystery. In addition, the climatic feedbacks of this radiation microphysical interaction will remain uncertain.

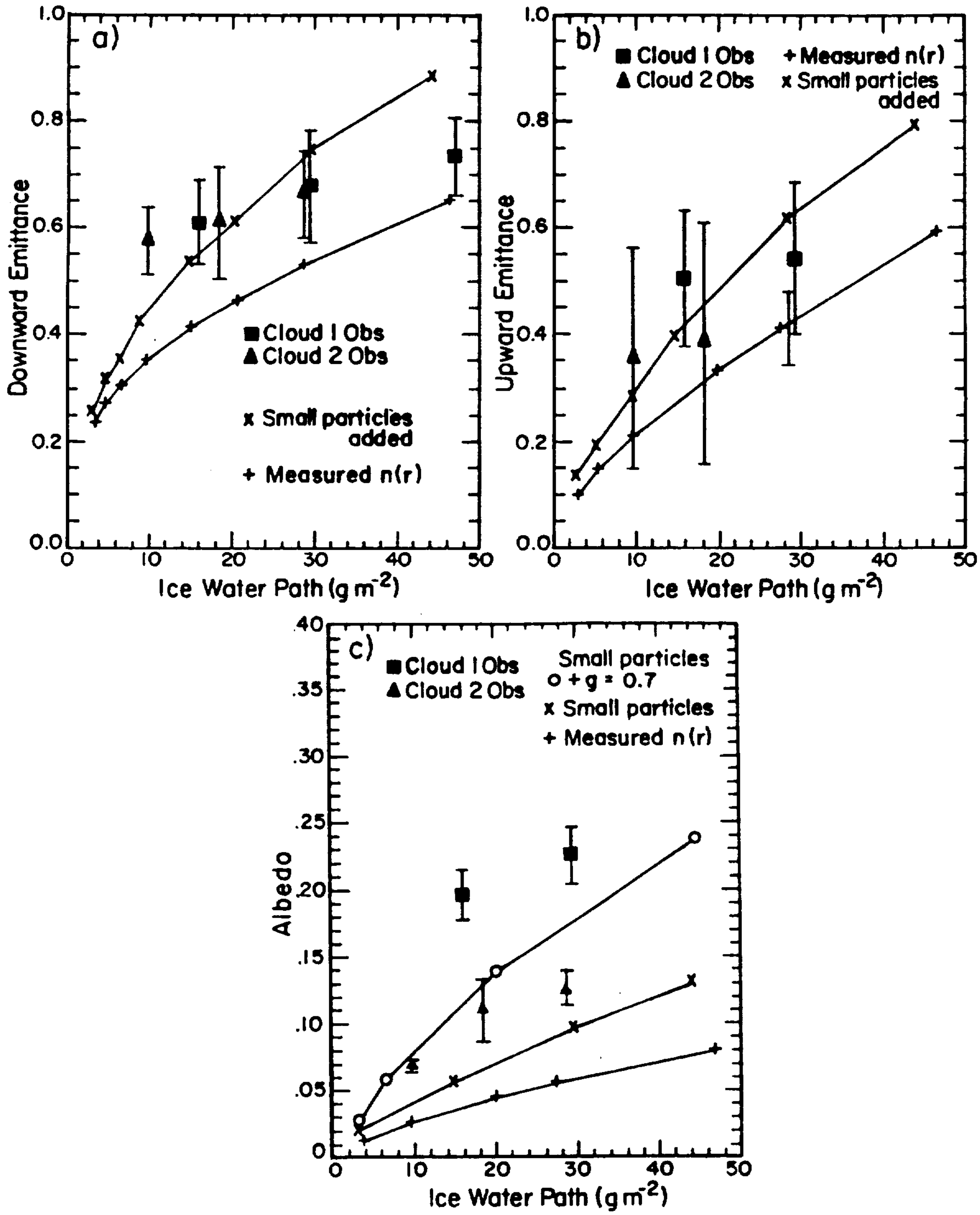


Figure 2: The variation of the downward emittance (a) the upward emittance (b) and the albedo (c) with IWP ($g \cdot m^{-2}$) computed from observed measurements for clouds 1 and 2 and the simulated emittances and albedos for the cloud cases as described in the text.

## ACKNOWLEDGEMENTS

This research was supported by the Atmospheric Sciences Section of the National Science Foundation under Contracts ATM-8812353 and ATM-8519160; the Department of Defense, United States Air Force Office of Scientific Research under Grant AFOSR-88-0143; and the Department of Defense Office of Naval Research Grant N00014-87-K-0228/P00001. The Mie solution computations were performed using the super computer facilities at Colorado State University Computer Center.

## REFERENCES

Ackerman, T. P., K.-N. Liou, F. P. J. Valero and L. Pfister, 1988: Heating rates in tropical anvils. *J. Atmos. Sci.,* **45,** 1606–1623.

Chou, M. -D., 1984: Broadband water vapor transmission functions for atmospheric IR flux computations. *J. Atmos. Sci.,* **41,** 1775–1778.

——, and A. Arking, 1980: Computation of infrared cooling rates in the water vapor bands. *J. Atmos. Sci.,* **37,** 855–867.

——, and A. Arking, 1981: An efficient method for computing the absorption of solar radiation by water vapor. *J. Atmos. Sci.,* **38,** 798–807.

——, and L. Peng, 1983: A parameterization of the absorption in the 15 $\mu$m spectral region with application to climate sensitivity studies. *J. Atmos. Sci.,* **40,** 2183–2192.

Cox, S. K., 1973: Cirrus Clouds and the Climate. it J. Atmos. Sci. **28,** 1513–1515.

Heymsfield, A. J. and K. M. Miller, 1989: The October 27-28, 1986, FIRE cirrus case study: cloud microstructure. *submitted to Mon. Wea. Rev.*

Kneizys, F. X., E. P. Shettle, W. O. Gallery, J. H. Chetwynd, Jr., L. W. Abreu, J. E. A. Selby, R. W. Fenn, and R. A. McClatchey, 1980: Atmospheric Transmittance/Radiance: computer code LOWTRAN 5. Report No. AFGL-TR-80-0067, Air Force Geophysics Lab, Hanscom AFB, MA., 200 pp.

Manabe, S. and R. F. Strickler, 1964: Thermal equilibrium of the atmosphere with a convective adjustment. *J. Atmos. Sci.* **21,** 361–385.

McClatchey, R. A., R. W. Fenn, J. E. A. Selby, F. E. Voltz, and J. S. Garing, 1972: Optical properties of the atmosphere, 3rd ed. AFCRL-72-0497, 108 pp.

Paltridge, G. W., and C. M. R. Platt, 1976: *Radiative Processes in Meteorology and Climatology,* Elsevier, 318 pp.

Preisendorfer, R. W., 1976: *Hydrological Optics V. Properties,* NOAA, PMEL.

Slingo, A. and H. M. Schrecker, 1982: On the shortwave properties of stratiform water clouds. *Quart. J. Roy. Meteor. Soc.,* **108,** 407–426.

Smith, Jr.,W. L., P. F. Hein and S. K. Cox 1989: The October 27-28, 1986, FIRE cirrus case study: *in situ* observations of radiation and dynamic properties of a cirrus cloud layer. *submitted to Mon. Wea. Rev.*

Stackhouse, Jr.,P. W. and G. L. Stephens, 1989: A Theoretical and Observational Comparison of Cirrus Cloud Radiative Properties. *Atmos. Sci. Pap. No. 452,* Colorado State University, Ft Collins, 117 pp.

Stephens, G. L. and P. Webster, 1981: Clouds and climate: Sensitivity of simple systems. *J. Atmos. Sci.,* **38,** 235–247.

——, P. W. Stackhouse, Jr., and P. J. Flatau, 1989: The relevance of the microphysical and radiative properties of cirrus clouds to climate and climatic feedback. *submitted to J. Atmos. Sci.*